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Ecosystem management tools to study natural habitats as wave damping structures and coastal protection mechanisms

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ABSTRACT

Tropical countries have island and continental ecosystems of great value for tourism, fisheries and also for their conservation development potential. These natural habitats, including among other beaches, seagrass beds, mangrove forests and coral reefs can dissipate wave energy acting as barriers against high waves and high water levels to eventually protect coastal infrastructure and communities. However, in recent decades, they have been subject to strong anthropic pressure and extreme events due to natural causes as well as to climate change. Therefore, the global trend is to understand the eco-systemic services that these natural environments can provide and their economic value in terms of reducing damages caused by coastal erosion and flooding. A methodological framework is presented in order to quantify the impact of natural ecosystems in coastal protection and their environmental assessment based on numerical models available in the literature. In addition to the methodology, a study of a typical Caribbean fringing coral reef and its response to different sea level rise and extreme events scenarios was conducted. The contribution of these efforts from a technological and scientific point of view, lies in the integration of different disciplines required to combine the physical properties of hydrodynamic studies with biological factors as an input to provide practical socio-economic and environmental solutions in those regions in which these ecosystems predominate. Furthermore, a numerical modeling tool to study wave energy dissipation, focusing the analysis on the impact of natural ecosystems (coral reefs) on coastal erosion and flooding was implemented. This information will help coastal managers and decision-makers understand the coastal protection services provided by nearshore habitats in order to improve and design new coastal development strategies under global change scenarios.

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1. Introduction

Nowadays coasts around the world are suffering from damage caused by the pressure they are subjected to due to factors such as population increase, density and urban development, global warming and sea level rise, pollution and deterioration of water quality (Day et al., 2012; Goreau and Hilbertz, 2005; Zhang et al., 2004), leading to the loss and degradation of coastal ecosystems and their ability to protect during extreme events and climate change scenarios (Baldock et al., 2014; Quataert et al., 2015; Storlazzi et al., 2011; Wild et al., 2011). This problem has been traditionally addressed through the implementation of rigid solutions or conventional engineering structures that seek to protect against the impact of waves, prevent flooding and mitigate coastal erosion (Lamberti et al., 2005) but with important ecological impacts on natural habitats (Day et al., 2012; Martin et al., 2005).

Despite the knowledge that exists about the ecosystem services provided by coastal ecosystems (e.g., food production, provision of nursery habitat, carbon sink, recreation and tourism, among others), the use of these habitats as coastal protection mechanisms has not been entirely adopted as an engineering practice and mechanism of adaptation to climate change. Nevertheless, in the last decade research and development of ecosystem-based approaches have advanced considerably, including an improved understanding of biophysical processes and the interaction between engineering structures and coastal ecosystems (Burcharth et al., 2015; Guannel et al., 2015). Additionally, the advances in valuation, modeling and mapping of ecosystem services as well as methodological frame-

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works and eco-engineering tools (Duarte et al., 2013; Sharp et al., 2016; Villa et al., 2011) have allowed the recognition of coastal ecosystems, from the engineering point of view, for their use as a coastal protection mechanism against coastal erosion and flooding (e.g., wave attenuation, shoreline stabilization, declining flood levels, etc.) in the face of global change (Ferrario et al., 2014; Guannel et al., 2015; Temmerman et al., 2013).

A few countries in Latin America (Mexico, Brazil, Chile, Colombia) have joined the idea of promoting interdisciplinary groups made up of biologists, ecologists, and engineers, to develop new strategies to replace and/or implement natural or hybrid solutions as unconventional coastal defense mechanisms, with possibilities for adaptation to climate variability and climate change (Burcharth et al., 2015; Silva et al., 2017). One of the key points on integrating processes from different research fields is about how biological characteristics (species composition and bottom roughness) from natural habitats are included into numerical models to account for wave energy dissipation and morphodynamic changes. Besides the contribution made by different authors (Duarte et al., 2013; Ferrario et al., 2014; Guannel et al., 2015; Quataert et al., 2015; Sharp et al., 2016; Storlazzi et al., 2005), there is still a lack of knowledge in understanding how different scenarios of coastal ecosystem degradation would impact coastal erosion/flooding and which management actions should be taken in order to preserve the protective services provided by the natural habitats.

For this reason, this study aims to develop and implement a methodological approach considering not only the role of biological factors in protecting coastal areas, but also the selection of an appropriate numerical model, able to describe the hydrodynamic and morphodynamic processes with a high level of accuracy. This information can be used to help decision-makers, coastal managers and other stakeholders understand the coastal protection services provided by natural ecosystems as well as to identify future research lines and coastal development strategies.

The present study is structured as follows: Section 2 presents a summary of the main ecosystem assessment frameworks and tools, which are available to scientists (engineers, biologists, and ecologists), managers and administrators to study coastal ecosystems as wave energy dissipation structures and coastal protection mechanisms. Section 3 presents a methodological framework for the study of coastal ecosystems based on the implementation of numerical models as mechanisms of analysis and decision making based on technical/scientific knowledge and in Section 4 some of these tools are applied (use of a numerical model) to understand the role played particularly by coral reefs in wave dissipation and its impact on coastal erosion and flooding. Finally, the discussion and conclusions are presented in Section 5 and 6 respectively.

2. Ecosystem assessment frameworks and tools

Based on the recent interest in the importance of valuing the ecosystem services provided by the different natural habitats (Duarte et al., 2013; Ferrario et al., 2014) a great variety of support tools that integrate ecology, economics and geography have emerged for managers and decision makers. In general, the main objective of these kinds of models is to produce functions using simplified underlying biophysical models or “ecological production functions” (Bagstad et al., 2013) that define how changes in an ecosystem’s structure and function are likely to affect the flows and values of ecosystems services across lands or seascapes. In Bagstad et al. (2013) a comparative analysis of 17 different ecosystem services tools is presented, with particular emphasis on describing each tool with its applications, modeled services, analytical approaches, inputs and outputs of the models as well as the time required to execute them. The comparison is made based on eight evaluative criteria, including: 1) Quantification and uncertainty. 2) Time requirements. 3) Capacity for independent application, 4) Level of development and documentation, 5) Scalability, 6) Generalizability, 7) Nonmonetary and cultural perspectives, 8) Affordability, insights, integration with existing environmental assessment. Some of those ecosystem services tools that can support an integrated ecosystem assessment to inform decision-making globally and at multiple scales are: Integrated Valuation of Ecosystem Services and Tradeoffs – InVEST (Kareiva et al., 2011; Sharp et al., 2016); Artificial Intelligence for Ecosystem Services – ARIES (Bagstad et al., 2011; Villa et al., 2011); LUCI – formerly Polyscape (Jackson et al., 2013); Multi-scale Integrated Models of Ecosystem Services/Marine Integrated Decision Analysis – MIMES/MIDAS (Boumans et al., 2015); Ecosystem Portfolio Model – EPM (Labiosa et al., 2013); among others. More details about each model, their performance, limitations and scale of modeling can be found in Bagstad et al. (2013).

It is also important to mention that, through its nearshore wave and erosion module, InVEST represents the only model among the aforementioned ecosystem modeling tools which fully addresses the contribution of natural habitats (e.g., mangroves, seagrass, coral reefs, oyster beds) to coastal protection. In this way, this tool is able to preliminarily quantify the impact of a particular wave boundary conditions on coastal erosion and flooding, considering a deterministic wave propagation model and taking into account the main hydrodynamic processes (e.g., wave energy dissipation due to wave breaking and bottom friction, wave setup, wave run-up). InVEST is an open source tool based on mapping and valuing goods and services provided by ecosystems as natural barriers against erosion and flooding (Guannel et al., 2015; Sharp et al., 2016). The valuation includes social preferences and allows the estimation of economic and social metrics based on the differences in damage due to erosion and flooding under different scenarios. Therefore, the cost of the avoided coastal erosion and further storm damages can be used as an indicator of the value of those coastal ecosystems.

Besides the fact that InVEST model may support management decisions demonstrating the protective capabilities of natural habitat, it also presents important limitations such as (Sharp et al., 2016): (i) non-linear processes in wave propagation are being ignored; (ii) extreme events such as storm surges are being underestimated; (iii) since the model is a 1D process-based tool, it ignores any complex wave transformations that occur offshore of the site of interest; (iv) an option to calibrate is not offered; (v) simple empirical equations are used to compute the wave profile, wave setup and wave run-up; and finally (vi) when erosion processes occur, the dynamic response and feedback between wave and bed profile during the storm is not taken into account. Despite all these disadvantages which may be overcome through the use of more robust hydrodynamic and morphological models as suggested in the methodology approach that is presented in Section 3, InVEST can still be applied for a first preliminary assessment of the hydrodynamic and morphodynamic performance of habitats.

With the implementation and improvement of all these ecosystem management tools, the aim is to identify coastal ecosystems with potential to be incorporated into traditional coastal protection schemes, based on analysis that allows them to evaluate under which conditions they can protect against erosion and coastal flooding. In this sense, the interaction between engineers, biologists and ecologists is of great importance as the knowledge of each discipline may contribute to optimize the functionality of these ecosystems and motivate ecological restoration processes. Similarly, inputs are obtained to quantify the degree of degradation or renewal of ecosystems before and after an extreme event and their impact on the ecosystem services they typically provide (Duarte et al., 2013; Ferrario et al., 2014) for comparison with traditional defense structures.

3. Methodological approach

Can nature help reduce risk from coastal hazards? Why is it important to preserve/restore the natural habitats like coral reefs, seagrass and mangroves? These questions seem to be obvious, but unfortunately just for ecologists and scientist who really know about the importance of those natural habitats and the ecosystem services they offer, especially in Latin America and the Caribbean, where natural defense structures are not yet well implemented and considered over traditional gray infrastructure (Silva et al., 2017). The role of us as engineers/scientists is to provide enough information and tools to help managers and decision makers to recognize the importance of natural habitats and the ecosystem services they provided and to evaluate the impact that their actions can generate over them. In this way, based on the different elements offered by the tools for ecosystem services analysis and valuation, a methodological framework is proposed for a better understanding on how the presence of different natural habitats modify the nearshore processes (e.g., wave and current attenuation), contributing to reduce shoreline erosion and flooding during storms and how coastal management can be improved to achieve a positive feedback that increases the ecosystem services.

This methodology then seeks the integration of biological characteristics of coastal ecosystems and physical processes, especially those related to the transformation of waves around natural structures, including sediment transport on beaches, which requires the use of more robust numerical models and their combined use, with the ecosystem decision tools for a successful management of ecosystem services. The different methodological steps, as summarized in Fig. 1, are described below:

3.1. Stage A – parametrization and physical characteristics

The first stage consists of the recognition of the predominant natural habitats in the area of interest (e.g., coral reefs, mangrove forests, seagrass bed, sandy/rocky beaches, estuaries, among other) and its level of interaction with the marine dynamics (waves, wind, tide and currents). Depending on the type of ecosystem and the available data in the study area, the topo-bathymetry (bottom profile) and roughness characteristics of the bottom surface (represented by frictional coefficients) are first obtained, which can generate important changes in hydrodynamic processes, depending on the level of structural stability, distribution and abundance of natural species and healthy state of the coastal ecosystem (Grant and Madsen, 1979; Hendriks, 2014; Mazda et al., 1997; Nelson, 1996; Pawlak and Maccready, 2002; Rosman and Hench, 2011; Young, 1989). Due to the complexity of heterogeneous bottom profiles, a major challenge for modeling wave transformation on coastal ecosystems is to select an appropriate parameterization for wave dissipation as a result of wave breaking and bottom friction. Several formulas exist to predict the rates of wave energy dissipation, but these are semi-empirical and must be calibrated through field data (Bricker et al., 2005; Lowe et al., 2005a, 2005b, 2005c; Reidenbach et al., 2006) or laboratory experiments (Dalrymple et al., 1984; Hu et al., 2014; Messaros and Bruno, 2011; Reidenbach et al., 2009; Samuel and Monismith, 2013).

Historically, several studies have been carried out to parameterize seabed roughness for homogeneous beds (e.g., sand ripples) where the scale of the bed features is at least an order of magnitude smaller than the wave orbital amplitude (Nunes and Pawlak, 2008). Pawlak and Maccready (2002) examined how oscillatory flows react to different roughness scales and showed that both the length scales and distribution of roughness elements introduce mechanisms that can enhance energy dissipation near bottom surface, suggesting that for accurate determination of bed friction processes, detailed characterization of bed roughness is needed along with effective parameterization schemes. Despite all the contributions to this field of research, parameterization of bed roughness is still not an exact science and still represents an important research topic since no reliable and well established formulae are yet available. For example, on reef flats with rough bottoms in shallow water, frictional dissipation has been considered a primary component of the total dissipation (Falter et al., 2004; Lowe et al., 2007, 2005a; Nelson, 1996); however, few studies have specifically linked the measured bottom roughness of a coral reef to observed rates of frictional dissipation (Huang et al., 2012; Lowe et al., 2005a). This discussion illustrates the need for robust parameterization schemes of bed roughness to estimate wave friction factors for complex seabed boundaries such as those presented by coral reefs (Nunes and Pawlak, 2008).

To account for wave energy dissipation caused by bottom friction, different frictional coefficients (f_w) are proposed in the literature to represent the roughness associated with the natural species (Lugo-Fernández et al., 1998b; Mazda et al., 1997; Nelson, 1996). In that way, mainly empirical approaches and constant coefficients without any physicalbasis have been used. A way to face this lack of knowledge is through laboratory experiments and the use of numerical models to come up with new physical parameterizations based on hydrodynamic conditions and the structural and biophysical characteristics of the bottom substrate (Husrin et al., 2012; Osorio-Cano et al., 2016; Samuel and Monismith, 2013).

Since bathymetry is a dominant variable which can explain most of the hydrodynamic processes including wave shoaling, wave reflexion and wave energy dissipation due to wave breaking and bottom friction, the better the bathymetry and seabed characterization, the better the representation of the physical processes from the numerical modeling in the next Stage.

3.2. Stage B – hydrodynamic and morphodynamic modeling

The rapid development of numerical models provides a large number of models to be used in engineering or environmental problems. Usually, selecting a suitable numerical model to solve a practical problem is a highly specialized task, requiring detailed knowledge on its capabilities and limitations (Chau and Chen, 2001). However, the new generation models have become more useful to a much wider range of end-users and for solving a wider range of problems, thus allowing to transform the knowledge of computational hydrodynamics into products that relate natural habitats with coastal ecosystem services. Four possible criteria for selecting the numerical model may be considered in the methodological framework: i) the user's purpose or problem specification, ii) the physical conditions in the user's specific problem, iii) the user's experience with the models, and iv) user's understanding about possible model results.

Hence, in order to help solving the management question about how natural habitats can help reduce risk from coastal hazards, the aim of Stage B is to identify an appropriate numerical model capable of describing the overall physical, hydrodynamic and morphological processes, depending on the degree of accuracy that is sought in the results and the type of analysis to be carried out (e.g., wave height dissipation, wave-induced setup, wave run-up, sediment transport, wave-current and wave-structure interaction). For this purpose, models based on wave energy conservation equation (Demirbilek et al., 2009; Gerritsen, 1980; Lowe et al., 2005a) are preferred because of the reduction of computational demand, getting faster results while making good and timely decisions. In coral reefs and mangroves ecosystems, the weakly-dispersive models based on Boussinesq-type water wave evolution equations (Nwogu and Demirbilek, 2001) are often used to model wave transformation in intermediate and shallow water depths. Other types of important models are the Non Linear Shallow Water Equations

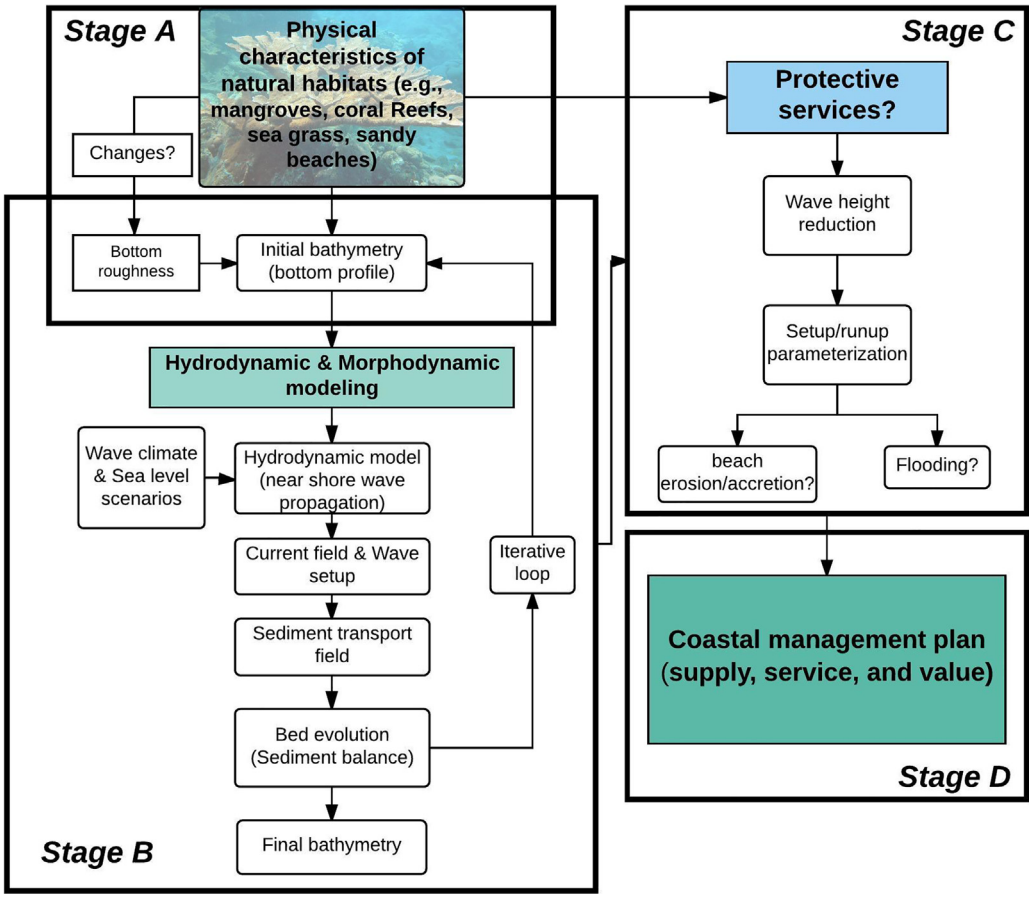

Fig. 1. Methodological approach in four stages to determine the level of protection offered by natural habitats as wave damping structures against coastal erosion and flood.

models like SWASH (Zijlema et al., 2011) or XBeach (Roelvink et al., 2009; Van Dongeren et al., 2012), which have been widely used around the world with applications in different types of ecosystems. In Stage B, the hydrodynamic models solve the flow equations along the bathymetric profile by considering the boundary conditions defined in Stage A, to propagate the waves from deep water to the coastline. As the waves approach the coast and the relative flow depth decreases, there is an increase in the mean sea level (wave-induced setup) as result of the radiation stress (Longuet-Higgins and Stewart, 1962), creating a pressure gradient that drives flow circulations. These wave-driven currents are responsible for the longshore/cross-shore sediment transport (including nutrients, plankton, larvae, etc.), generating successive changes in the bottom profile until a sediment balance is reached and a final bathymetry is obtained. Since surf and swash zone sediment transport processes are very complex (Bellotti and Brocchini, 2005; Longo et al., 2002; Pomeroy et al., 2015; Torres-Freyermuth et al., 2007; Trouw et al., 2012), it is necessary for the predictive models to describe the overall physics as accurately as possible in a reasonable computational time (Roelvink et al., 2009).

3.3. Stage C – coastal protection services

After running the numerical model, it is possible to quantify the protection services (Bagstad et al., 2013; Sharp et al., 2016) provided by the different habitats and their capacity to respond to an extreme wave climate event or important changes on the ecosystem properties and structural variation of benthic communities (Burcharth et al., 2015; Narayan et al., 2016). The provided services are characterized on the basis of the ability of the habitat to protect or serve as a barrier by reducing the wave height and water levels in the nearshore region leading to less erosion and flooding along the coastline (Ferrario et al., 2014; Guannel et al., 2015). At this stage, it is important to perform a sensitivity analysis of the different physical and biological variables involved during the numerical modeling (Stage A and B) to evaluate the model response to these new scenarios. For example, alteration of bottom cover (roughness) would lead to important changes in the degree of exposure to erosion or flooding, especially when there are vulnerable communities living close to the ecosystem, who may see their physical stability altered in the face of extreme events or climate change scenarios. Hence the key task of the numerical modeling is to generate a complete picture of the effect of the input variables (like the short wave friction factor, f_w) to generate enough data (graphs, tables, indicators, etc.) which are suitable for an accurate decision making process by managers, environmental authorities and scientific community.

3.4. Stage D – management actions

Recent research advances require the integration of ecosystems into coastal engineering solutions and their conversion into engineering practices that promote sustainable requirements for the proper management of coastal erosion and flooding (Burcharth et al., 2015). It is for this reason that the information generated in the previous stages is expected to be used to help coastal managers and decision-makers understand the coastal protection services provided by nearshore habitats and design new coastal development strategies and regulation plans (Agardy et al., 2011; Narayan et al., 2016). The decisions that will be made will be based on the services that the ecosystem is able to offer not only for protection against erosion and flooding, but also the fact of having a healthy and diverse habitat that provides support to communities, biodi-

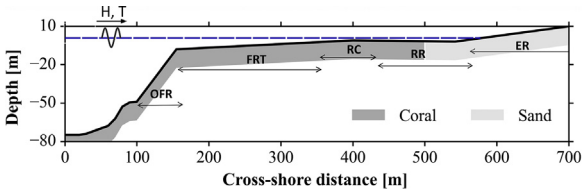

Fig. 2. Coral reef profile and main geomorphological characteristics: outer fore-reef (OFR); fore reef terrace (FRT); reef crest (RC); rear reef (RR) and emergent reef (ER).

versity of species, tourism and promotes the sustainable economic development of the communities that live there (Duarte et al., 2013; Ferrario et al., 2014).

4. Implementation of the proposed methodology

In Latin America there is still a lack of knowledge about how and to which extent coastal marine habitats, such as coral reefs, mangroves and seagrass beds, may function as natural breakwaters, attenuating waves and storm surges. Understanding the role that these nearshore habitats have in protecting coastal communities will provide new insights on how to face climate change and growing development pressure through more adaptive solutions. To address this, a coral reef was selected as an exemplary coastal ecosystem to implement the proposed methodology, including a sensitivity analysis about the effect of coral reef degradation (changes on coral reef roughness) on wave height dissipation, wave run-up and coastal erosion.

4.1. Coastal ecosystem characteristics

4.1.1. Bathymetric profile

Due to the high complexity of the bathymetry and wave dynamics characteristic of reef environments and unlike waves on sandy beaches, the transformation of waves across natural reefs represents a highly complex process that includes factors like refraction, shoaling, reflection, energy dissipation due to breaking waves and bottom friction, highly turbulent flow, wave set up and wave energy shifts into lower frequencies (infragravity waves). The dissipation due to wave breaking is conditioned mainly by the reef bathymetry and water depth, while dissipation due to bottom friction depends on the structural characteristics of the reef surface (e.g., type of species, density and distribution).

Based on the general characteristics of coral habitats in the Colombian Caribbean (Díaz et al., 2000; López-Victoria and Díaz, 2000; Sánchez, 1995), a simplified cross section of a fringing coral reef was defined. The reef profile and the main geomorphological features are shown in Fig. 2, which includes: (i) a sloping outer fore-reef (OFR) with a slope of 1:1.3 (37°) and between 8 and 50 m deep, (ii) a fore-reef terrace (FRT) with depths varying from 1 to 8 m and slope of 1:35 (1.6°), (iii) a shallow top reef crest (RC) between 1 and 2 m deep, (iv) a reef flat or rear reef (RR) and the emergent reef (ER) composed by a sandy beach with a slope of 1:20 (<3°). The total length of the reef profile including the beach is about 700 m.

4.1.2. Coral reef roughness

The flow structure within benthic boundary layers may have important consequences on the ecology of benthic organisms and in turn on how these organisms affect the hydrodynamics occurring within their environment (Lowe et al., 2008). Considering the complexity of species distribution in coral reefs, several authors have proposed different models to simplify the basic reef communities and ecological zonation based on physical parameters like wave exposure and water depth (Geister, 1977; Graus and Macintyre, 1989).

Table 1
Bottom surface characteristics and its associate wave friction factor (f_w).

Criteria	fw (friction factor)
Smooth sandy beaches	O(0.01)
smooth rock or coral pavement	0.1–0.2
Live coral or dead non-eroded (75%-100% coral cover)	0.3–0.6
Very high bottom roughness (100% coral cover of healthy massive and branched coral species)	1.0

In this step, the methodology is focused on the selection of the appropriate wave friction coefficient (f_w) which better represent the physical interaction between the biological characteristics and hydrodynamic processes. As mention before, coral roughness is rarely homogeneous and characterized by wide scales of roughness (Monismith, 2007), but for complex and heterogeneous bottoms, only limited knowledge is available on how to predict frictional coefficients. The wave flow over a rough boundary has typically been approached considering homogenous bottom roughness (Nunes and Pawlak, 2008), which results in parameterizations based on a characteristic roughness scale. The determination of f_w requires the direct or indirect measurement of bed shear stress or the measurement of wave energy loss over a known distance (Nelson, 1996). In Sheppard et al. (2005) roughness values were assumed to vary over the range, $f_w = 0.1$ to 0.2, where 0.1 was associated with smooth rock or coral pavement, and $f_w = 0.2$ with a healthy coral reef, based on the measurements performed by Nelson (1996) at Jhon Brewer Reef in Australia. However, due to the experimental limitations and difficulty to measure in coral reef environments, this coefficient has been estimated as a "tuning" parameter through numerical modeling calibration process to obtain the best agreements with field data. Quataert et al. (2015) achieved a f_w value of 0.3 after numerical model calibration of XBeach model with field data collected at Roi Namur Island on Kwajalein Atoll in the Republic of Marshall Islands, smaller than the f_w value of 0.6 reported by Van Dongeren et al. (2013) on a fringing coral reef (Ningaloo Reef in Western Australia) described with high coverage of branching corals. On the other hand, Monismith et al. (2015) with observations of wave dissipation on the south fore-reef of Palmyra Atoll, reported a wave friction factor $f_w = 1.80 \pm 0.07$, nearly an order of magnitude larger than values previously found for reefs. The reef was characterized be nearly 100% coral cover with a very complex canopy structure and healthy reefs, hence the authors argued that this high value is an effect of the structural complexity of the reef and the fact that the effective friction factor for canopies can be larger than 1. Based in the literature and despite the fact that there is still not enough and unique reference values to associate friction factors with particular coral reef species and bottom roughness characteristics, a general association (somehow arbitrarily) is made in Table 1.

In order to evaluate the impact of changes in coral reef roughness on coastal erosion and flooding, the idealized coral reef profile was divided in two section: a non-erodible coral surface (x = 0–500 m) and an erodible sandy bed (x = 500–700 m) (see Fig. 2). For coral reef section, a wide range of short wave friction coefficients values ranging from $f_w = 0$–1.0 were selected to be implemented into the numerical model. Values of $f_w = 1.0$ have not yet reported in the literature, however it is considered as an hypothetic reference value to evaluate the effect of having such a high wave friction factor in the main physical processes studied here. The idea is to evaluate how coral reef degradation/restoration would impact coastal erosion and flooding in order to determine the protective services provided by the coral reef ecosystem.

4.2. Hydrodynamic and morphodynamic modeling

To study the wave energy attenuation along the reef and to evaluate how corals can dissipate waves and reduce coastal erosion and flooding, an open source model called XBeach (Roelvink et al., 2009) is used (version 1.22.5002). The model is selected considering its application on coral reefs environments and coastal erosion problems, giving advantages over some other numerical models already mentioned, especially due to its capacity to compute the natural coastal response during time-varying storm and hurricane conditions, including dune erosion, swash motion and breaching. The model has been validated with a series of analytical, laboratory and field test cases with accurate results in a reasonable computational time as described below.

4.2.1. Model description and governing equations

XBeach solves the coupled time-dependent 2DH (horizontal) equations of wave action propagation and dissipation, and the 2DH equations of conservation of mass and momentum, with applications on morphodynamics and hydrodynamic processes, including short wave transformation processes (refraction, shoaling and breaking waves), infragravity waves, wave generation, propagation and dissipation, wave setup, unsteady currents, and also overwash and flooding. The model has been extensively validated for natural and artificial submerged structures and sandy coastlines with series of analytical, laboratory and field test cases, and offers the required two-dimensionality to study storm impacts of up to a few days of duration. The model can be applied to areas extending several kilometers in the longshore and about a kilometer in the cross-shore, giving the opportunity to include the 2D effect on hydrodynamic processes and longshore/cross-shore sediment transport (Nederhoff et al., 2015; Roelvink et al., 2013; Trouw et al., 2012; Zimmermann et al., 2012). The model has two modes: a hydrostatic and a non-hydrostatic mode. In the hydrostatic mode, the short wave amplitude variation is solved separately from the long waves, currents and morphological change, saving computational time, with the expense that the phase of the short waves is not simulated. A more complete model is the non-hydrostatic mode, which is essentially the nonlinear shallow water equation with dispersion terms and without a wave-action driver. Smit (2008) implemented into the existing XBeach model a non-hydrostatic module, using a numerical scheme based on Stelling and Zijlema (2003). Since XBeach is a depth-averaged model, the non-hydrostatic module has only one vertical computational layer, in contrast to other non-hydrostatic models like SWASH with several layers (Zijlema et al., 2011). With the XBeach non-hydrostatic mode it is possible to apply phase resolving methods for both high and low frequency motions on the individual wave scale and to model the non-linear wave field evolution and dispersion. On the other, hand the breaking processes and the short wave run-up on the beach can be calculated with more accuracy but higher computational demand (Quataert, 2015).

The model solves the depth averaged non-linear shallow water (NLSW) equations in a Generalized Lagrangian Mean (GLM) formulation and is based on the wave action balance given by Eq. (1):

$$\frac{\partial A}{\partial t} + \frac{\partial C g_x A}{\partial x} + \frac{\partial C g_y A}{\partial y} + \frac{\partial C_\theta A}{\partial \theta} = -\frac{D_w + D_f + D_v}{\sigma} \quad (1)$$

where C_g represents the wave group velocity in the direction of the subscript x (cross-shore), y (alongshore) and θ (directional); D_w, D_f *and* D_v are dissipation terms for respectively waves, bottom friction and vegetation and σ is the representative radian wave frequency. A is the wave action and represents the wave energy density (E) in each directional bin for its representative radian wave frequency ($A = E/\sigma$).

The time dependent action balance is solved on the time-scale of wave groups. In this way, the swash motion due to infragravity waves that are forced by the groups could be simulated.

The bottom friction dissipation term (D_f) in Eq. (1) is calculated as (Van Dongeren et al., 2013):

$$D_f = \frac{2}{3\pi}\rho f_w \left(\frac{\pi H_{rms}}{T_{m01} sinhkh}\right)^3 \quad (2)$$

where ρ is the water density, f_w is the short wave friction coefficient, T_{m01} is the mean spectral period, k the wavenumber, h represents the local water depth and H_{rms} is the root-mean-square wave height. For a detailed description of the XBeach model and further equations, reference is made to the works of Roelvink et al. (2009).

4.2.2. General applications on coral reefs

Although the model was originally derived for mild-sloping sandy beaches, with some additional formulations, XBeach has been applied in reef environments (Pomeroy et al., 2012; Van Dongeren et al., 2013) and proved to accurately predict hydrodynamic processes related to a reef environment. The additional formulations include the effect of higher bottom roughness on incident wave decay through the incident wave friction coefficient (f_w), as outlined by Van Dongeren et al. (2013).

In Van Dongeren et al. (2013), the low-frequency wave dynamics on a fringing coral reef were investigated using XBeach. The model was validated based on short waves, infragravity waves and water level measurements obtained from a field study at Ningaloo Reef in Western Australia. They founded that short waves dominated bottom stresses on the fore-reef and near the reef crest, while inside the lagoon, the infragravity waves were dominant. The water levels, infragravity and short wave heights were sufficiently reproduced by calibrating the friction coefficients.

Stockdon et al. (2014) evaluated the model competence to predict wave-induced setup, incident swash, and infragravity swash to test the application of run-up parameterizations under extreme conditions. In a similar way, Quataert et al. (2015) used the XBeach model (in both Hydrostatic and non-hydrostatic mode) to quantify the effects of different coral reef characteristics (reef flat width, fore reef slope, reef roughness) on wave run-up, wave-induced setup, wave height dissipation and potential coastal hazards caused by wave-driven flooding and how these effects may be altered by sea level rise, higher waves and coral reef degradation (lower bed roughness) considering projected climate change scenarios.

4.2.3. Model setup

XBeach was run over a one-dimensional reef profile with an idealized bathymetry obtained from a typical fringing reef in the Colombian Caribbean Sea (Fig. 2). The model was set up with a variable cell size (x-axis direction): 10 m from the deepest point to the starting reef slope (from x = 0 to x = 100 m), 5 m from the reef slope to the reef crest (from x = 100 m to x = 400 m), and 1 m for the inner rear reef and the sandy beach. The total number of computational cells was 371.

In accordance with the mean and extreme wave characteristics reported in the Colombian Caribbean Sea (Bernal et al., 2016; Osorio et al., 2016) and coastal flooding hazard related to storm surges (Andrade et al., 2013) a total number of 96 regular wave tests by varying the offshore boundary conditions and the short wave friction coefficients were considered. Each case consisted of a combination of four (4) heights (H = 1, 2, 3 and 4 m), three (3) periods (T = 6, 8 and 13 s) of the incident waves, two (2) elevation of the mean sea level above the still water level (z_{s0} = 0 and 2 m, associated with the occurrence of a possible storm surge event and high tide conditions) and four (4) short wave friction coefficients (f_w = 0.0, 0.1, 0.3 and 1.0). The latest were selected according to pre-

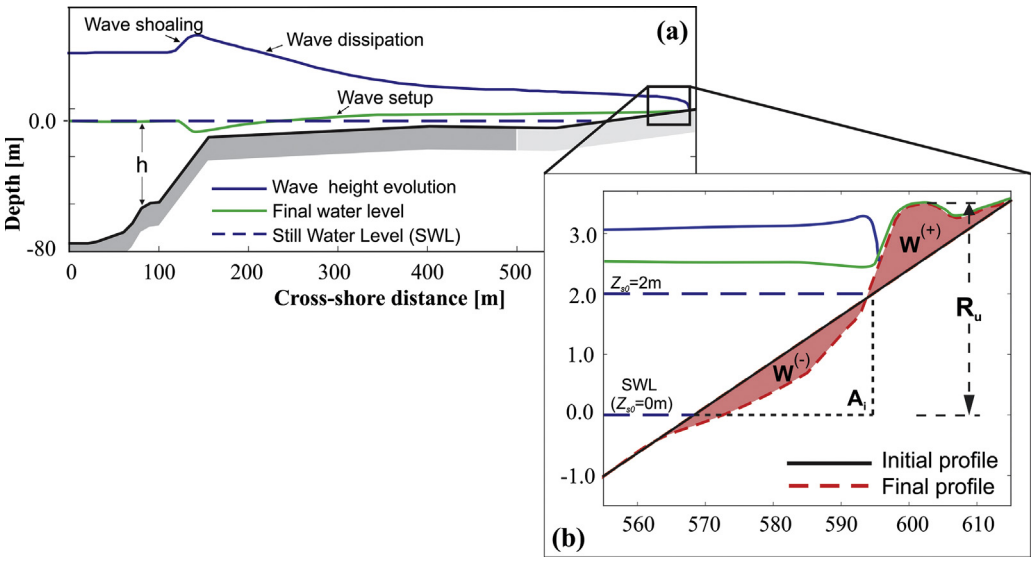

Fig. 3. 1D cross-shore profile of a typical fringing reef including the main hydrodynamic processes: wave height evolution, wave-induced setup (η_{setup}), wave run-up (R_u) and the eroded sandy area after numerical simulation ($W^{(-)}$ or $W^{(+)}$).

vious values reported in the literature as mentioned in Section 4.1.2 and considering the variation range (f_w between 0 and 1) suggested by the XBeach manual (Roelvink et al., 2015).

Elevation z_{s0} is defined as the water depth over the still water level (see Fig. 3b), which for the study case and under low tide conditions is located 1 m over the reef crest (h_r = 1 m). It means that z_{s0} = 2 m is associated with a water depth of h_r = 3 m over the reef crest.

After a sensitivity analysis (not shown here) resulting in no significant differences in the final beach profiles, a simulation time associated with a storm duration of 6 h with a variable time step determined based on a given maximum Courant number (CFL = 0.7 by default) was defined. The computational time was approximately 15 min per run in an 8 GHz Intel Core i5 @ 8 GB RAM iMac.

4.3. Protective services provided by the coastal ecosystem

The idea behind this study is to specify how new scenarios, or management actions, represented as changes in frictional coefficients possibly resulting from reef degradation/phase shifts, may affect/improve the capacity of coastal habitats to protect against flooding and coastal erosion compared to a baseline condition. Fig. 3 shows the cross-shore bathymetric profile and the main physical variables and hydrodynamic processes studied. The vertical excursion of the water level relative to the still water level was defined as R_u, following the methodology proposed by Holman (1986). Furthermore, the amount of sand eroded or transported along the beach profile, is defined as the negative or positive difference, $W^{(-)}$ or $W^{(+)}$, between the initial profile (black line in Fig. 3b) and the beach profile at the end of the numerical simulation (red dashed line in Fig. 3b). $W^{(+)}$ should be equal to $W^{(-)}$ (principle of mass conservation) since no longshore sediment transport is considered for this 1D analysis.

4.3.1. Wave height reduction & wave run-up

The effect of the change in mean sea level on the wave height envelope along the reef is shown in Fig. 4. There is evidence of a strong wave shoaling for the highest wave heights in the transition zone between the outer fore-reef (OFR) and for reef terrace (FRT) followed by a wave height decay on account of bottom friction until reaching the reef crest where most of the waves break. Considering the distance between the reef crest and the beach (150 m approx.), some dissipated waves after shoaling and breaking, continue propagating until shoreline where they are completely dissipated. Along the FRT and rear reef (RR), the wave energy dissipation related to bottom friction is of a great importance and is directly linked with the substrate characteristics (bed roughness) and the level of physical integrity of the coral colonies. Different authors stated that on reef flats with rough bottoms in shallow water, frictional dissipation has been considered as a primary component of the total dissipation (Falter et al., 2004; Lowe et al., 2005a; Nelson, 1996). Indeed, wave dissipation rates from bottom friction in large roughness environments are on average larger than dissipation rates due to breaking (Lentz et al., 2016; Monismith et al., 2015; Rogers et al., 2016).

The abrupt changes in the slope of the coral reef bathymetry act as a mechanism to control the total energy of the incoming waves, where the significant wave height is dissipated between 77 and 94% for a mean water level z_{s0} = 0.0 m (Figs. 4a and 5a) and between 25 and 80% for an extreme scenario represented by a storm surge event (z_{s0} = 2.0 m, Figs. 4b and 5a). Similar amount of wave energy dissipation (75–85%) was obtained by Lugo-Fernández et al. (1998a) across a Caribbean fringing-barrier reef and by Sheppard et al. (2005) where an average wave energy dissipation rate of 80% was found. In our study, the wave height dissipation was calculated as $Diss\,[\%] = (H_o - H_{sw})/H_o \times 100$, where H_o is the offshore incident wave height defined at the inlet boundary and H_{sw} is the nearshore transmitted wave height in shallow water at the toe of the beach (x = 550 m). This point is selected as a reference to account for the influence of the coral reef roughness over the transmitted waves at the rear reef, which in conjunction with currents are responsible for the sediment transport and beach profile evolution. It should be noted that these results were obtained assuming a constant value for the short wave friction coefficient of f_w = 0.3, which should represents healthy coral cover conditions (Sharp et al., 2016). As expected, the highest dissipation values are obtained for the scenarios associated with z_{s0} = 0 m, with the highest wave height and shortest period (Fig. 5a). This occurs because the larger waves begin to break before reaching the reef crest, conditioned by strong changes in the relative water depth h/H. The lowest percentages in wave height dissipation are given for scenarios with increase in mean sea level, low wave heights and high periods (Fig. 5a).

As mentioned before, during high mean water levels (z_{s0} = 2.0 m, Fig. 4b), the wave energy dissipation is drastically reduced and

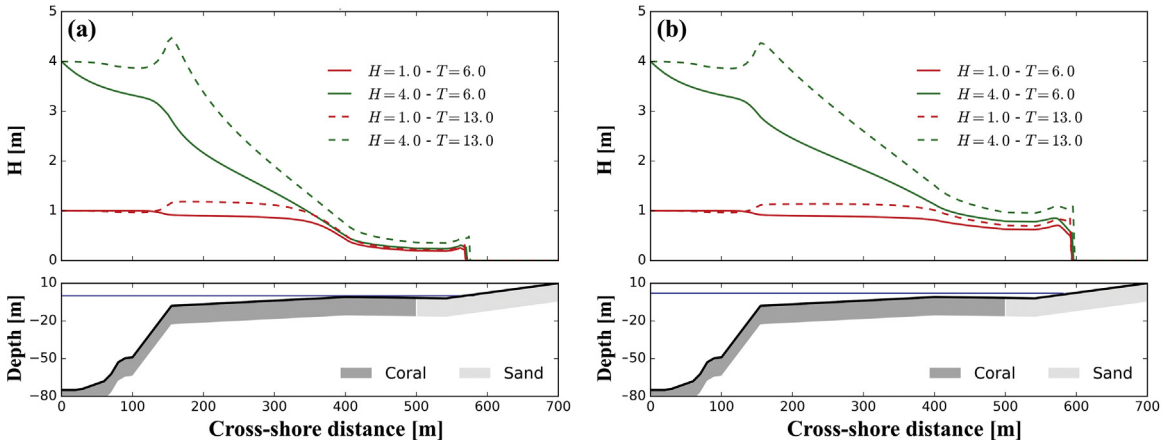

Fig. 4. Numerical results for wave height evolution (H) considering (a) z_{s0} = 0.0 m and (b) z_{s0} = 2.0 m. Results assuming f_w = 0.3.

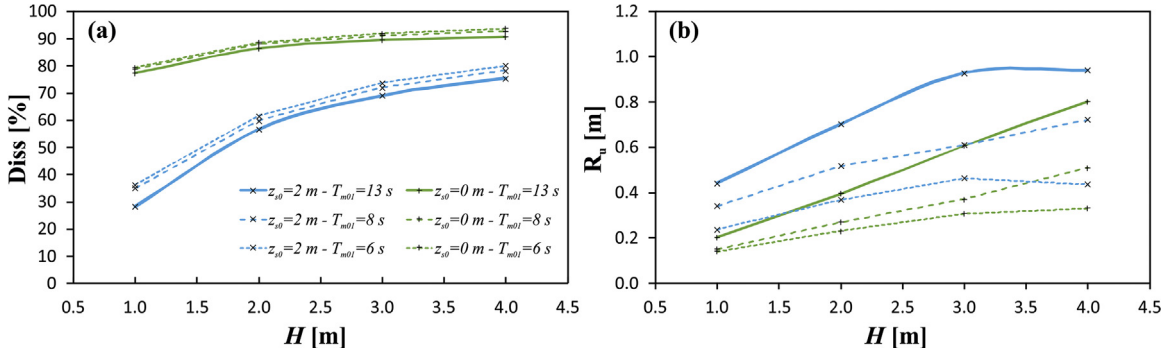

Fig. 5. (a) Wave height dissipation (Diss) and (b) wave run-up (R_u), for different sea water levels (z_{s0} = 2.0 m in blue color and z_{s0} = 0.0 m in green color), wave height (H) and wave periods. Results assuming f_w = 0.3 for all the simulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher values of wave height are obtained on the beach, which could lead to more severe erosion and flooding scenarios. Fig. 5b presents the wave run-up levels at the shoreline for all propagated cases. It is observed that wave run-up increases (R_u > 0.80m) for the highest wave height (H), wave period (T) and mean water level (z_{s0}), representing high risks to the integrity of the coastal ecosystems and possible physical infrastructure.

Fig. 6 shows the results of a sensitivity analysis, considering the effects of possible bottom surface changes through the use of different wave friction coefficients (f_w = 0.0, 0.1, 0.3, and 1.0), in order to evaluate the wave-induced setup (Fig. 6a) and wave height evolution (Fig. 6b), for one of the most extreme cases (H = 4 m, T = 13 s, z_{s0} = 2 m). For this particular case, the submerged depth of the reef crest is crucial for the behavior of the wave setup along the reef where minimum (set-down) and maximum setup are obtained before and after the reef crest respectively (Fig. 6a), when non-frictional dissipation is considered (f_w = 0.0). Opposite behavior occurs when using f_w = 1.0. Moreover, in Fig. 6b the differences on wave height are clearly seen for the whole range of f_w values, where the higher wave height values at the toe of the beach are obtained for the minimum f_w values and vice versa as expected.

Fig. 7 shows the percentage of the incident wave height dissipation (Fig. 7a) and run-up (Fig. 7b) for all cases associated with T = 13 s and z_{s0} = 0 m. The results indicate differences between 20 and 45% in the wave dissipation (Diss) obtained, being the greater differences associated with the lower wave heights. As for run-up (R_u), values up to 3 times higher are obtained for the highest wave height (H = 4 m). Similar results (not shown here) are obtained for other scenarios of wave periods and tidal level.

Since the model may be used as a tool to account for the total amount of avoided erosion or inundation and subsequently being used to quantify the number of people protected and the value of avoided property damages, the choice of the short wave friction coefficient values in a numerical model is of a great importance and should be based on a previous knowledge of the study area and the benthic characteristics mentioned before.

4.3.2. *Nearshore bed erosion*

The model was used to account for the effect of wave height and bottom friction on wave erosion that takes place after a storm event and/or extreme wave climate scenario. Fig. 8 presents an example of the beach profile evolution for the case H = 4 m, T = 13 s for different f_w and z_{s0} values. The continuous black line corresponds to the initial beach profile, while dashed lines represent the evolution of the beach profile obtained at the end of 6 h simulations. The major changes in the profile occur precisely for the scenario associated with z_{s0} = 2 m and f_w = 0.0 (dark blue dashed line in Fig. 8b), where there is a strong erosive process at the base of the beach, whose sediment is accumulated in a swash bar towards the top of the beach. Under real conditions, all the sediment transport generated under these scenarios would be affected by longitudinal currents that are expected to occur in the shallower zone after wave breaking, associated mainly with the oblique incidence of wave propagation and wave height gradients (not simulated here). In that way, under a high sea level scenario, the sediments could be removed from the control volume and enlarge the erosion processes in the swash zone.

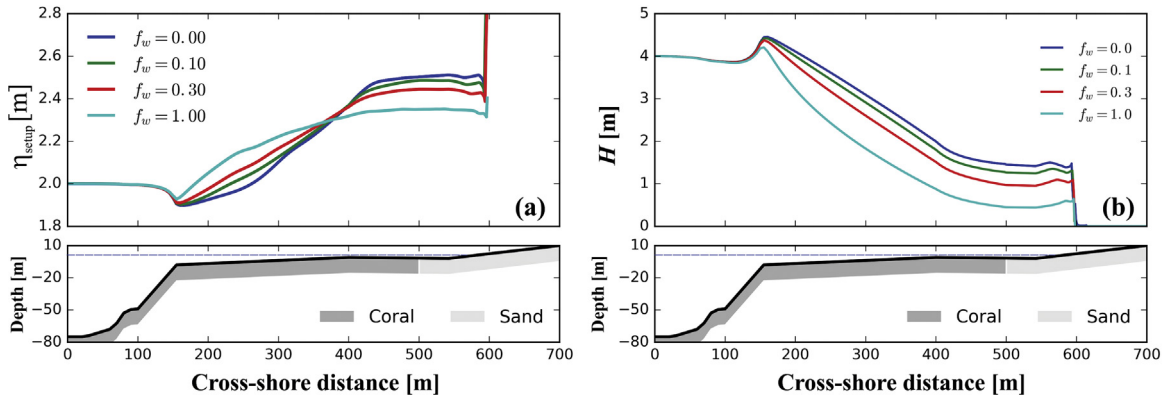

Fig. 6. Numerical results for (a) wave-induced setup (η) and (b) wave height evolution along the coral reef for different wave friction coefficients (f_w). Case: H = 4 m, T = 13 s, and z_{s0} = 2 m.

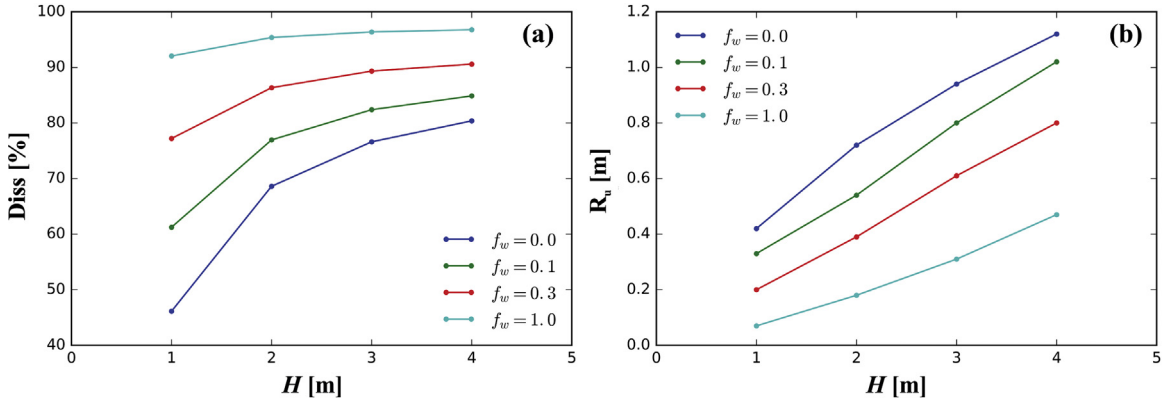

Fig. 7. (a) Wave height dissipation (*Diss*) and (b) wave run-up (R_u) for different short wave friction coefficients (f_w) and wave heights. Cases associated with T = 13 s, and z_{s0} = 0 m.

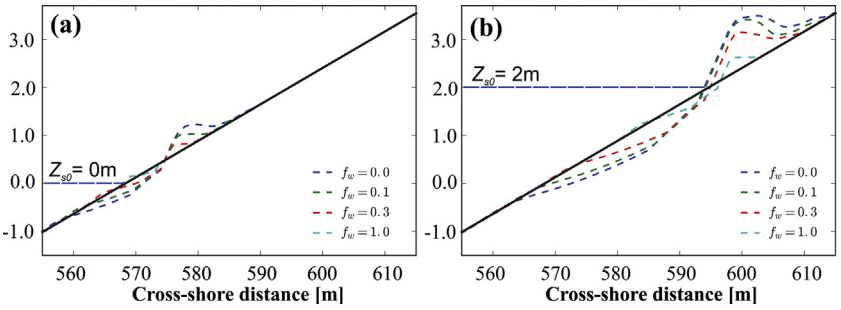

Fig. 8. Beach profile evolution after numerical simulation (dashed lines) considering (a) z_{s0} = 0 m and b) z_{s0} = 2 m for all short wave friction coefficients. Case: H = 4 m, T = 13 s.

Since we are not looking for absolute values of beach erosion and due to the fact that numerical models still need improvement specially in the swash zone, a non-dimensional parameter called "Erosion Area Factor" defined as $\lambda = A_r/A_i$ [−] was introduced, where A_r is the amount of sand ($A_r = W^+$ or W^-) that was removed (or transported) by the wave-induced cross-shore currents, calculated as the positive (or negative) values from the difference between the bed profile at the end of the simulation and the initial bed profile (red and black line respectively in Fig. 3b); and $A_i = 26.3\ m^2$ is an influence area defined between the sea water level conditions (as illustrated in Fig. 3b by the black dashed triangle) and used as a reference to compare between different cases. Therefore, the parameter λ indicates the proportion of the affected beach area that is susceptible for erosion depending on the different sea water level conditions and wave friction coefficients for each regular wave scenario.

Fig. 9 shows the results obtained for all selected wave and sea water level cases evaluating the effect of the short wave friction factor (f_w) on the beach erosion in the swash zone. For the scenarios associated with the lower sea water level (z_{s0} = 0 m, left panels in Fig. 9), beside the fact that most of the energy is dissipated between the reef crest and the beach, there is an important proportion of sand that is susceptible for erosion when the friction factor decreases and the wave height and wave period increase, where

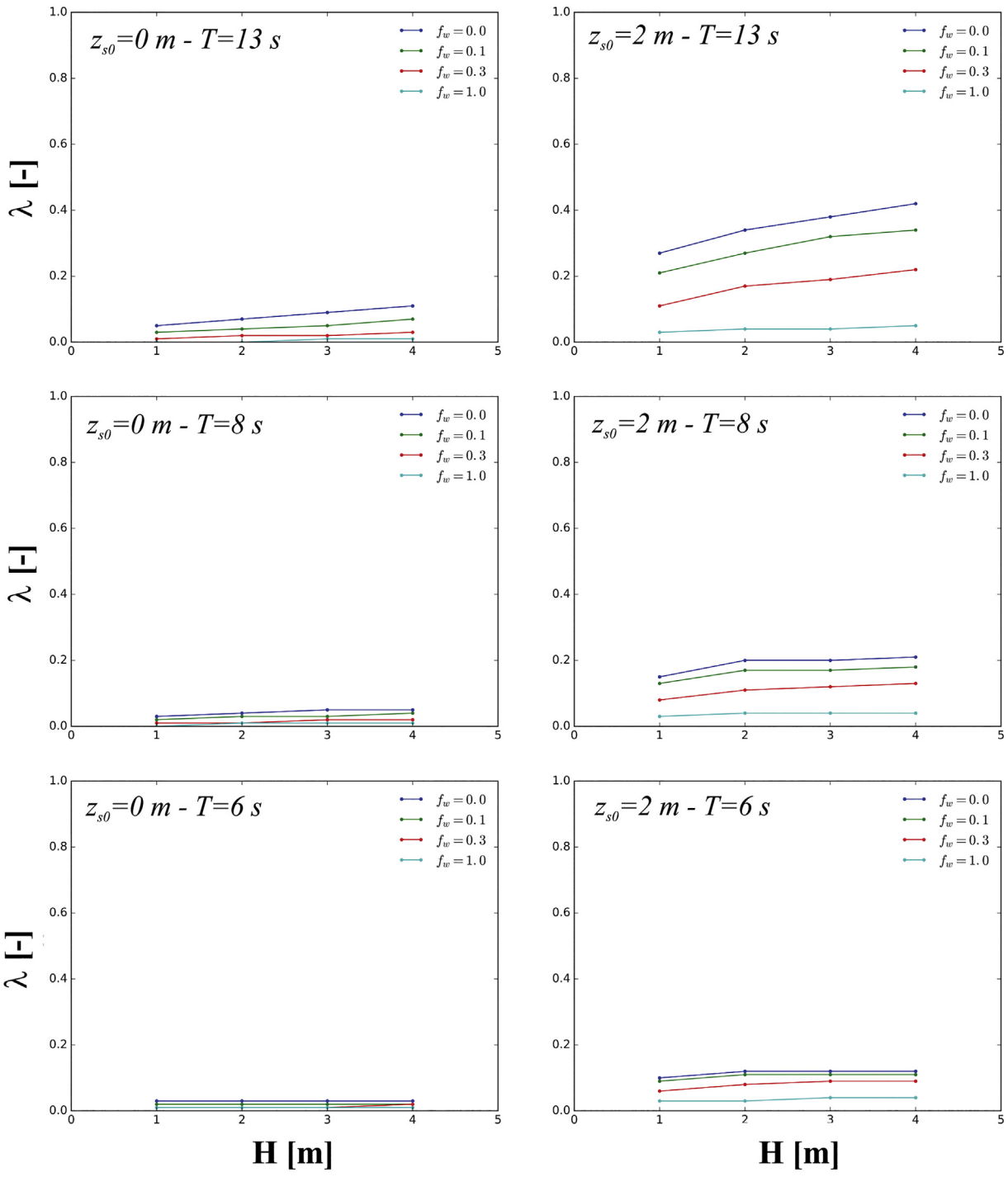

Fig. 9. Proportion of the amount of sand that is susceptible to erosion represented by the Erosion Area Factor (λ), depending on the different sea water level conditions (z_{s0} =0 m and z_{s0} =2 m in left and right panels respectively), wave periods (T = 13, 8, 6 s from top to bottom respectively) and wave friction coefficients for each regular wave scenario.

the most critical case (λ = 0.11) corresponds to H = 4 m, T = 13 s and f_w = 0.0. When the results for f_w = 1.0 are analyzed, not important differences are observed between the scenarios. On the other hand, the results associated with a high tide level (z_{s0} = 2 m, right panels in Fig. 9), indicate that there is a great influence of the short wave friction coefficients on wave erosion where λ takes values ranging from 0.04 to 0.12 for the lower period (T = 6 s) and between 0.05–0.42 for the higher period (T = 13 s). This means that at higher wave heights and lower f_w values, under storm surge episodes, a greater amount of sediment is possible to be re-suspended and removed away from the system.

5. Discussion

Coral bleaching events, which are likely to become more frequent due to ocean acidification and global climate change (Hoegh-Guldberg, 1999), have been shown to kill off corals, decreasing hydrodynamic roughness (Sheppard et al., 2005; Wild

et al., 2011). These processes will reduce bottom friction, which would increase wave heights, wave-induced run-up, and wave-driven flooding (Baldock et al., 2014; Quataert et al., 2015; Sheppard et al., 2005). This is in particular important since the bottom profile of a reef will be only maintained if reefs are kept healthy and if coastal and land management practices are designed to minimize/avoid stressful conditions to coral reefs (e.g., reducing threats such as poor water quality, overfishing, sedimentation) and thus preserving or even improving its capacity to dissipate wave energy. As mentioned by Baldock et al. (2014), changes in water depth over the reef flat may occur from loss of coral from breakage, erosion or any other stressors, which directly reduces reef flat elevations and can be assessed by considering them as a pseudo-sea level rise, modifying bottom stresses and reef hydrodynamics. In this way, since coral reefs are live systems that can, to some extent, keep up with natural hazards (e.g., storm surge conditions and extreme events) and thus potentially be able to offer services by adapting to evolving scenarios, decision makers should employ natural systems to maximize the benefits provided by them, ensuring that decision-making does not generate a negative impact.

Within this methodological framework, the XBeach model was used exemplarily as one of the possible tools to quantify the potential impact of frictional coefficient reduction due to reef degradation on the protection performance of coral reefs in terms of wave attenuation and reduction of beach erosion as compare to healthy natural habitats. The results indicate high wave dissipation values (77–94%) for a current sea level scenario ($z_{s0} = 0$ m) which is drastically reduced to values between (25–80%) in a storm surge scenario ($z_{s0} = 2$ m). These results were obtained under the assumption of $f_w = 0.3$ associated with healthy coral conditions, whose drastic decrease affects not only the amount of wave energy dissipated but also the degree of coastline affectation (changes in beach profile) and wave run-up (R_u) on the swash zone. These results, provide insights on how coastlines surrounded by coral reefs may be susceptible to the effects of climate change and coastal ecosystem degradation.

Knowing the importance of choosing an appropriate wave friction factor, and beside the fact that it is still an open research question, especially for coral reefs environments, the results from this study underline the importance of preserving and managing bottom roughness.

In shallow water, i.e. when the bottom roughness elements are comparable in height to the depth of the water, the wave energy dissipation caused by the form drag of these “canopy” elements is dominant (Huang et al., 2012; Lowe et al., 2007; Monismith et al., 2015). Since there is not a real consensus in the literature about the use of the wave friction coefficient to represent the complexity of heterogeneous bottoms, there is a challenge for scientists to improve how the wave energy dissipation is calculated, considering the physical processes and biological characteristics of the natural species, their distribution, density, shape, flexibility among other biophysical parameters as well as the most relevant parameters of the prevailing waves and currents.

Beside the fact that the methodological framework was applied in a coral reef environment, this approach can also be implemented to other natural habitats like oyster reefs or vegetation meadows and mangroves, by using an appropriate coastal wave model, able to represent the complex hydrodynamic processes associated with wave-structure interaction, like SWAN-VEG module from SWAN model (Suzuki et al., 2012). The latest assumes a group of cylinders as representation of vegetation, based on the ecosystem characteristics such as height, width, density, and drag coefficient, and is used to determine the magnitude of the dissipation term to quantify the wave energy behind the vegetation field. Following this approach, the numerical models as an integral part of the ecosystem management tools allow to generate the necessary inputs (maps, reports, graphs) for decision makers to evaluate, assess and quantify the impact that their actions may generate over natural ecosystems, improving flow services that are vital for the human being, including the production of goods (e.g., food and shelter), recreation, biodiversity, human development and sustainable ecosystem conservation. Those management decisions include for example marine spatial planning to determine efficient zoning of coastal resources uses, definition of new marine protected areas to allow for management of fishing and other local activities, land use planning with restrictions on development in areas covered by sensitive areas like mangroves and coral reefs, new sewage treatment requirements to improve coastal water quality, among others.

Wave-induced water levels can be a direct threat to people, infrastructure, and ecosystems; however they are not generally included in the analysis of coastal hazards (Stockdon et al., 2014). This is why recent advances in research require the integration of ecosystems into coastal engineering solutions and to convert them into common practices that promote sustainable requirements for proper management of coastal erosion and flooding (Silva et al., 2017). Coastal storms damage properties and the difference in damages due to habitat can be considered as an indicator (not studied here) of the value of natural ecosystems in providing protection to properties from extreme events and climate change scenarios (Duarte et al., 2013). In practice, InVEST (Kareiva et al., 2011; Sharp et al., 2016) is probably one of the most accessible and widely used tool for estimating risk reduction from natural habitats; however it still has limitations that can be overcome by improving the interaction between the natural habitats and the hydrodynamic conditions. InVEST could be used for the last stage of the methodological approach by using the valuation module to quantify the protection provided by those habitats in terms of the avoided damages to property due to erosion from waves and flooding, based on the market value of properties in the area. Other authors like Van Zanten et al. (2014) have proposed an analytical framework to enable a comprehensive evaluation of the coastal protection function and value which can be incorporated to a proper coastal management plan as suggested in Stage D, based on the main findings of the present study.

In comparison to the growing number of reef hydrodynamic studies, much less research has been done with XBeach in the area of morphodynamics and sediment transport on and behind coral reefs. However, considering that the model has been validated in sandy coastlines and with the confidence that the numerical model was successfully reproducing the coral reef hydrodynamics (Roelvink et al., 2015), the results obtained from this study, beside being encouraging, might also contribute to understand the influence of bottom friction on beach erosion behind coral reefs. New research in this area should be done with more validation data from laboratory and field measurements, especially in 2D scenarios where oblique waves and longshore currents are of great importance to account for longshore sediment transport, opening the possibility to estimate bed scour and to compute the volumetric sediment loss based on scour rate and storm duration. The existing ecosystem management tools may be improved by considering the dynamic feedback that takes place between wave and bed erosion as it occurs, by using process-based methods to account for hydrodynamic process between wave conditions and natural habitats.

6. Conclusions

This study provides a general presentation of some of the main available ecosystem management tools to quantify goods and services provided by ecosystems as natural barriers against coastal erosion and flooding. Each of these tools can be used to estimate the risk reduction afforded by natural habitats; however, few of

them are process-based approach that include wave propagation models to account for wave-structure interaction near the coast where most of the critical physical process occur. In this way, a new methodological framework with a process-based approach is presented, based on the selection of a more robust numerical model to improve the estimation of coastal ecosystem services related specifically to the protection against coastal flooding and erosion. Additionally, the study highlights the importance of considering an appropriate wave friction factor to account for wave energy dissipation due to bottom friction and its impact on the ecosystem services, particularly in a typical coral reef environment connected to a sandy beach. Hence, this research might help to solve the question about how effective a coral reef ecosystem could be in providing protection against coastal erosion and flooding, evidencing how hydrodynamic conditions may change in complex systems with high bottom roughness, providing insights for coastal managers and decision-makers to consider strategies in favor of natural habitats restoration and the use of coastal ecosystems in eco-engineering solutions for coastal protection over traditional grey infrastructure.

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